Conference or Workshop Item:

Koksal, Koray, Lembessis, V. E., Yuan, Jun orcid.org/0000-0001-5833-4570 et al. (1 more author) (2021) Field Distributions and Atom Trapping in Focused Axially-Shifted Counter-Propagating Light Beams. In: The 11th International Conference on Metamaterials, Photonic Crystals and Plasmonics, 20-23 Jul 2021. (Unpublished)

Field Distributions and Atom Trapping in Focused Axially-Shifted Counter-Propagating light Beams

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Abstract

We highlight the properties and the physics of a special kind of structured light, namely when two counter-propagating Laguerre-Gaussian optical beams interfere with their focal planes shifted axially by a finite distance d. We distinguish between two different situations: the back-to-back (d<0) and face-to-face (d>0) cases and show how these lead to finite ring lattices, Ferris-wheels and conveyor belts between the focal planes. Furthermore, even in the case of shifted Gaussian beams a new all-optical atom trapping environment is shown to arise due solely to the scattering force on atoms at near resonance when the beam waists are of sub-wavelength dimensions. Our findings are discussed with reference to sodium atoms.

1. Introduction

The discovery of light beams carrying orbital angular momentum (so-called twisted light beams) and their realization using novel experimental techniques such as spiral phase plates or computer-generated holograms have led to new applications involving the optical trapping and cooling of atoms, free-space communications, optical cryptography and in general novel light-matter interactions. Not only light beams have been shown to carry OAM but also matter waves as, for example, beams of electrons, neutrons or even neutral atoms and ions. Theoretical and experimental analysis on the effects of twisted light beams on atoms have shown that the OAM of light can be used as a tool to bring out different degree of translation and rotation of atoms depending on the OAM contents, which led to the possibility of using twisted light in the field of manipulation of atoms. The superposition of twisted light beams, namely co- or counter-propagating axial-shifting beams, involves strong interference effects leading to optical lattices, Ferris wheels, new kinds of optical trapping [1]. We have recently emphasized the optical environment in which axially-shifted counter-propagating twisted or untwisted light beams are set up [2]. Here we focus on such multiple beams which are strongly focused.

This talk intends to highlight some striking features of interference of strongly focused counter-propagating twisted light beams. Strong focusing, enhances contributions from the Gouy and curvature phases in interactions with atoms and for beam waists in the sub-wavelength regime value even in the case of untwisted beams the scattering force produces complete atom trapping. We show that axial-shifting as a parameter plays an important role in the generation of the interference patterns and the characters of the optical forces acting on the atom..

2. Axial-shifting induced optical forces

If the beam waist and wavelength are of the same order, it is possible to observe novel properties of the scattering and dipole forces and by virtue of the interference effects, new kinds of optical trapping regions and optical lattices are generated.

2.1. Dipole Force due to the interference effect

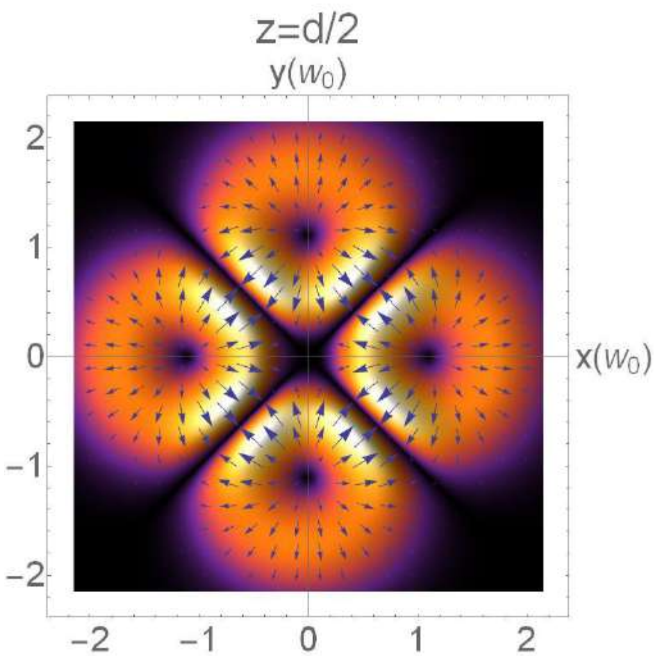

Figure 1: The dipole force in-plane distribution due to counter-propagating doughnut beams with focal planes coinciding at z=d/2. Here the winding numbers are both ℓ=2

and this leads to the four lobes pattern shown with arrows representing the local direction of the force.

Figure 1 displays the dipole force arising from the superposition of two counter-propagating doughnut beams for beam waist $w_0=\lambda$, winding number $\ell=2$ axial shift $d=3w_0$ and the plot is in the plane z= d/2.

From figure 1, we can conclude that by changing the beam waist, the axial shift and the winding number we are able to change the characteristics of the dipole force. By reducing the beam waist to values as low as sub-wavelength values, we can change the directions and magnitudes of the local force vectors. The change in the shifting parameter d (for example d<0) leads to the change in bright and dark regions which means that the locations of the trapping potentials will be reversed. OAM varies the number of lobes and change the size of the dark region.

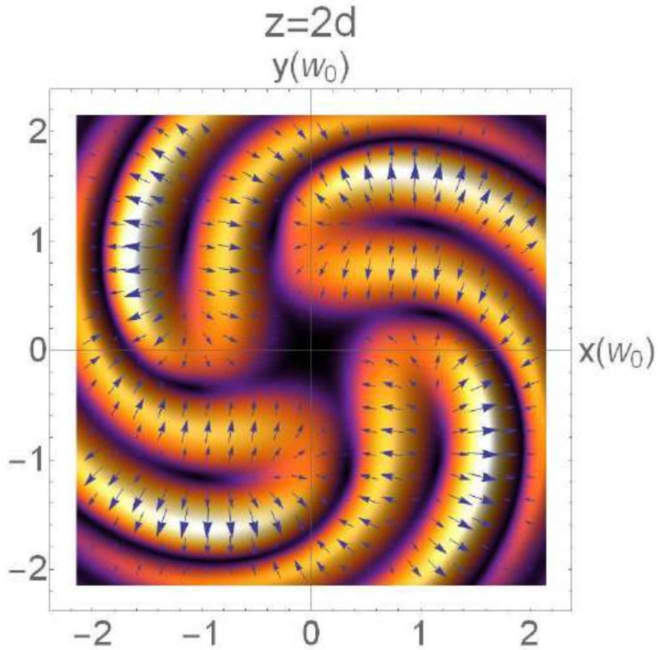

Figure 2: The dipole force distribution evaluated in the plane z=2d. The parameters are the same as those in Fig. 1.

Figure 2 shows the dipole force distribution in the plane z=2d. The spiral geometry is due to the interference effects between inner and outer rings of the beams. If the z plane is chosen as larger than 3d, we find that the doughnut rings completely separated from each other. Note that the direction of the force vectors are towards to the center for the inner ring while those in the region of the outer rings have outward directions.

2.2. Scattering Force and Dipole Force when omitting interference effects

The scattering (or dissipative force) is a result of the gradient of the phase function of Laguerre-Gaussian beam. The scattering force can be evaluated using the same parameters used in the dipole force. In order to elucidate the effects of the shifting of the focal planes we concentrate on the independent beam approximation, where forces, both dipole forces and scattering forces from individual beams simply add. Once more we choose $\ell_1=-\ell_2$.

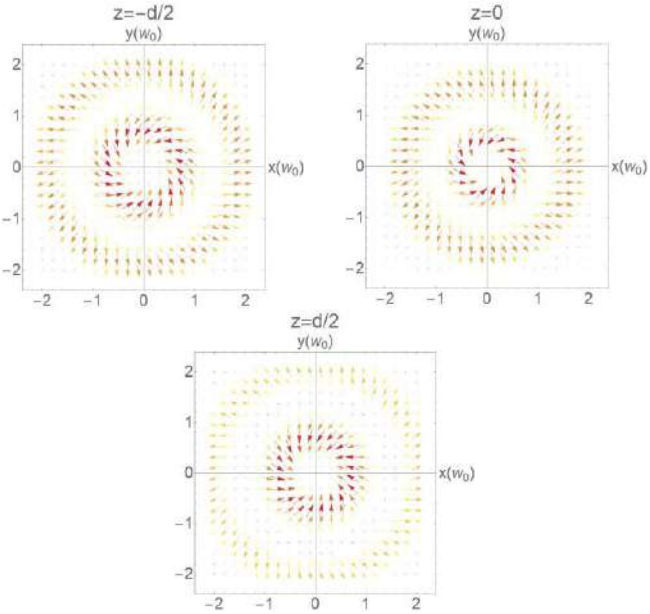

Figure 3: Total of scattering and dipole forces obtained from the superposition of two counter-propagating doughnut beams where $\ell_1=-\ell_2$. Top, middle and bottom rows indicate the force vector distributions z=-d/2, z=0 and z=d/2, respectively.

The results for this case are shown in Figure 3. The inner ring of the vectors are due to the scattering force, while the outer ring are due to the dipole force.

3. Conclusions

We have explored the field distributions and the optical forces acting on atoms due to interaction with counter-propagating axially-shifted doughnut beams. In view of the fact that the recoil energy of Na atoms is in the scale of 10^{-29} J, we have found using realistic parameters that the corresponding trapping potential due to the scattering force alone in the x-y plane to be sufficiently deep to trap Na atoms. By varying the OAM content, the beam width and the focal plane shift d, it is possible to design and modify the geometry of the optical forces to attain desirable all-optical trapping potentials for use where single atoms and ions are needed for quantum technology applications.

References

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